Real-Time Systems in Automotive Applications: Vehicle Stability Control

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Abstract

This paper will investigate the application of embedded systems in current state of the art vehicle stability systems. For clarification purposes, the focus will be on those systems similar to ESP (electronic stability program) originally developed by Bosch in 1995. The overall emphasis of this paper will be to examine these automotive systems from an embedded systems point of view.

There are several key issues pertaining to embedded systems in vehicle stability control addressed throughout this paper. The first issue addressed will be state of the art electronics used in these systems including controllers, actuators, and sensors; then followed by the issue of operation of the stability control electronics and the way they interact with other vehicle electronics such as engine control. The third issue is the control algorithm and architecture that operates the system.

This paper will also analyze the limitations of these vehicle stability systems, possible sources of system failure, as well as what is being done to prevent such failure. In addition, this paper will investigate the future trends in vehicle stability control and try to determine future developments in vehicle stability control. Finally, the advantages and disadvantages in terms of safety and performance are discussed.

Keywords

Vehicle Stability Systems; Embedded Systems; Vehicle Safety; Real Time Systems; Automotive Applications

Introduction

Embedded systems play a critical role in vehicle stability control systems. By examining current state of the art systems like Bosch's ESP in great detail, the impact of embedded systems for this automotive application can be understood.

One of the biggest technological advances that have made systems like Bosch's ESP possible is the wide availability of automotive electronics. Electronics such as electronic control units, steering angle sensors, wheel sensors, lateral acceleration sensors, yaw rate sensors, and engine controllers have made the development of vehicle stability systems possible. In addition, the ability to connect these electronic components over a high speed network has aided in the development of these vehicle systems.

The electronic components of ESP work to stabilize a vehicle in a critical situation and prevent it from steering are out of control. The system operates through a series of high speed digital messages sent from the sensors to the control unit, and finally to the actuators. In a matter of milliseconds, these components assess the status of the vehicle, determine any necessary corrective action, and initiate that corrective action by applying the brakes and controlling engine torque [Van Zanten et al. (1999)].

The fundamental control algorithm utilizes the data flow among all of the electronic components to assess the vehicle's behavior, determine if any changes need to be made to the vehicle, and control the components responsible for altering the vehicle's behavior. The primary goal of the control algorithm is to compare the actual behavior of the vehicle with the desired behavior, as well as to determine what needs to be done to make those behaviors equivalent [Van Zanten et al. (1999)].

Electronic systems have greatly improved the safety and performance of vehicles. With such systems, there are some inherent limitations and problems including increased risk that must be addressed by system designers. Because these systems are critical for safety, special steps must be taken to ensure the systems reliability and fault tolerance.

In the past twenty years, the automotive industry has seen vehicle safety going from anti-lock brakes, to

traction control, and finally to stability control. Stability control is a technology people could have never dreamed of 40 years ago. However, recent developments in other vehicle applications such as brake-by-wire and steer-by-wire are continuing to push the capability and performance of vehicle stability control forward.

Finally there are many advantages of a system like ESP, including vehicle safety and improved control in inclement conditions. While the introduction of electronic control into more and more vehicle systems offers significant improvements and advantages, there are inherent risks and problems associated with this progression. Issues related to decreased driver control and consumer awareness need to be addressed when vehicle electronic systems like ESP are in development.

ESP: Past, Present, and Future

The history of vehicle stability control can be followed simply by investigating Bosch's contributions to vehicle electronic systems over the past 25 years. Bosch has led to the development of vehicle stability controlled by introducing 3 fundamental systems into the market: anti-lock braking (ABS), traction control (TCS), and electronic stability program (ESP) ["Bosch Braking Systems", http://www.boschautoparts.co.uk].

The development of ESP began in 1978 when Bosch introduced the world's first anti-lock braking (ABS) system ["Bosch Braking Systems", http://www.boschautoparts.co.uk]. ABS was the first step in vehicle stability control. By means of an electronic controller integrated with the brake hydraulic modulator, this system increased vehicle stability during heavy braking by preventing the wheels from locking up ["Bosch Braking Systems", http://www.boschautoparts.co.uk]. This system is especially effective when braking on slippery surfaces.

ABS functions by using the wheel speed sensors to monitor each wheel and send that information to the central ECU. If the ECU detects an indication of wheel lock-up based upon the speed of each wheel, it will use the hydraulic modulator to adjust the braking force applied to the desired wheel [Cage (1999)]. The greatest level of benefit will occur when ABS is utilized on slippery surfaces. There are three primary objectives of ABS: reduction of stopping distances, improvement on stability, and steerability during braking [Cage (1999)].

The next step in the development of vehicle stability control was the introduction of the traction control system (TCS) by Bosch in 1987 ["Bosch Braking Systems", http://www.boschautoparts.co.uk]. The goal of traction control is to stabilize the vehicle during acceleration by preventing the wheels from spinning out of control. TCS also seeks to improve traction of the wheels while accelerating. TCS used all of the same components as previous ABS systems with the addition of engine management [Sauter (1999)].

By selectively applying the brakes to wheels that are slipping, TCS is able to increase the amount of traction for that wheel. This is especially important when the wheels are on surfaces with varying levels of friction [Sauter (1999)]. In addition to using the brakes to control traction while accelerating, TCS also utilizes engine management to control the vehicle. By communicating with the engine controller, the TCS system is able to control the amount of torque that is sent to the wheels. If the system detects that a wheel has almost no traction with the road and is simply spinning, the TCS system is able to greatly reduce the torque delivered to that wheel. The engine management system adjusts the amount of torque by controlling the airflow to the engine (throttle control), the fuel injection, and the spark timing [Sauter (1999)]. By adjusting all of these elements, TCS is capable to greatly increase or decrease the amount of torque delivered to a wheel.

Engine management is a tremendous advancement in vehicle stability because it greatly has reduced the dependence on braking systems, thus the amount of wear and tear on the brakes as well as the size of brakes necessary on the vehicle [Sauter (1999)] are reduced.

The following table shows the evolution of vehicle stability control systems over the past 25 years, the way how each system was built based upon the previous one by indicating shared components and how each system differs by listing the additional components that enable the next evolution in vehicle stability.

Bosch took vehicle stability from preventing skidding while braking to stabilizing the vehicle on slippery roads. Vehicle stability technology will continue to move forward with more developments in automotive electronics.

Technology	Year	Past Components	New Components
ABS – Anti-Lock Braking System	1978	Disc Brakes	Hydraulic Modulator, ECU, wheel speed sensors
TCS – Traction Control System	1987	Disc Brakes, ECU, wheel speed sensors	Engine ECU
ESP – Electronic Stability Control	1995	Disc Brakes, ECU, Engine ECU, Wheel Speed Sensors	Yaw Rate sensor, Lat. Accel. Sensor, Steering Angle Sensor

FIG. 1 VEHICLE STABILITY TIMELINE ["BOSCH BRAKING SYSTEMS", HTTP://WWW.BOSCHAUTOPARTS.CO.UK]

Vehicle Stability Manufacturers

There are four major manufacturers of vehicle stability control systems: Bosch, Continental-Teves, TRW, and Delphi. Bosch and Continental-Teves predominate the majority of the market share, with Delphi and TRW the relative latecomers developing systems only within the past two years ["Braking Systems", www.trw.com, Electric Steering Systems, www.delphi.com].

All four manufacturers follow a similar architecture. The basis for all current vehicle stability control systems is of course Bosch's ESP system that was originally introduced in 1995 [Braking and Chassis Systems, www.boschusa.com]. Current state of the art systems from all of these manufacturers all include the same basic components: hydraulic modulator w/ECU, wheel speed sensors, steering angle sensor, yaw rate sensor, lateral acceleration sensor, engine controller, transmission controller, acceleration pedal sensor, and brake pressure sensor. The greatest amount of variation in systems manufactured by different companies will reside in selection of the individual components rather than in the overall architecture. The following table displays the current manufacturers of vehicle stability systems, when they first entered the market, their system, and the various vehicle markets where their system can be found.

Manufacturer	Year	System Name	Markets
Bosch	1995	ESP–Electronic Stability Program	Mercedes, Lexus, Audi, BMW, VW
Continental-Teves	1998	ESP–Electronic Stability Program	BMW, Chrysler, Ford, Jaguar, Nissan, Toyota
Delphi	2002	TRAXXAR	Cadillac, GM Vans
TRW	2002	VSES–Vehicle Stability Enhancement System	Cadillac Escalade

FIG. 2 VEHICLE STABILITY MANUFACTURERS [BRAKE-BY-WIRE TECHNOLOGIES, WWW.CONTI-ONLINE.COM, BRAKING AND CHASSIS SYSTEMS, WWW.BOSCHUSA.COM, "BRAKING SYSTEMS", WWW.TRW.COM, ELECTRIC STEERING SYSTEMS, WWW.DELPHI.COM]

Components of ESP

A vehicle stability program requires the interaction of several electronic modules, sensors, and actuators. The most fundamental piece of the ESP system is the ECU or Electronic Control Unit. The figure below shows an ESP ECU from Bosch with a built-in hydraulic modulator for brake activation. Early versions of ESP used an ECU that is separated from the hydraulic modulator, but in an effort to reduce weight, size, and cost, an ECU was developed using hybrid ceramic substrates much smaller in size than earlier ECU's. Using ceramic substrates has also greatly improved the ECU's thermal robustness and overall lifetime [Van Zanten et al. (1998)].

FIG. 3 ESP HYDRAULIC MODULATOR WITH ADD-ON ECU [Braking and Chassis Systems, www.boschusa.com]

The ECU is the "brains" of the vehicle stability system. The ECU is responsible for gathering data from the sensors and using that data to calculate any adjustments that need to be made to the brake pressure or engine torque. A more detailed explanation of system operation will be given later.

A common design for current state of the art ESP ECU's is a dual microprocessor layout. A typical microprocessor used in ECU's of this type is the Intel 8XC196JT [Van Zanten et al. (1998)] specifically designed for automotive applications that is an 8-bit microprocessor with 256 kilobytes of ROM and 8 kilobytes of RAM and has PWM outputs (pulse width modulation), A/D inputs on operating range from -40 to 125°C [www.intel.com/design/auto/chassis.htm]. The chip also has a built-in watch dog timer to reset the device in the case of software or hardware failure ["The TTP Protocols", http://www.vmars.tuwien.ac.at/projects/ttp/ttpmain.html]. Such fault tolerance protection is extremely critical in a system such as ESP. ESP that is a hard real-time system and system faults or failures are not acceptable. The results could be catastrophic in the event of a system failure.
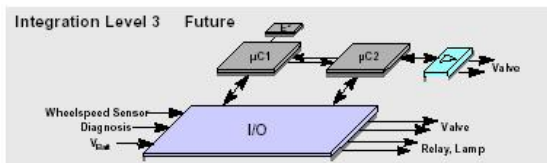
FIG. 4 ECU LAYOUT WITH DUAL 8XC196JT MICROPROCESSORS [Van Zanten et al. (1998)]

The vehicle stability system also requires the use of many different sensors in order to determine the actual state of the vehicle as well as the desired state of the vehicle based upon the driver's input.

To determine the speed of the vehicle and the amount of pressure applied to each wheel, the system uses wheel speed sensors. The information from the wheel speed sensors is used to calculate the actual vehicle speed as well as the amount of slip that each wheel is experiencing. The amount of tire slip is calculated by comparing the speed of the wheel with the actual vehicle speed. Tire Slip = wheel speed–actual vehicle speed [Van Zanten et al. (1999)]. The actual vehicle speed is determined by assessment on the speed of a non-driven wheel.

FIG. 5 WHEEL SPEED SENSOR [Braking and Chassis Systems, www.boschusa.com]

The system also needs to be capable of monitoring the desired motion of the vehicle from the driver's input. To measure the driver's input, a steering angle sensor and acceleration pedal sensor are used. The steering angle sensor is mounted behind the steering wheel on top of the steering column and measures the position of the steering wheel. There is also a sensor for the acceleration pedal to measure the desired speed/ acceleration of the vehicle. See Fig. 3 below.

FIG. 6 STEERING ANGLE SENSOR [BRAKING AND CHASSIS SYSTEMS, WWW.BOSCHUSA.COM]

A fundamental development in automotive electronics that facilitate the creation of ESP is the ability to measure the vehicle's rotation around a vertical axis. Imagine a pole going through the top of the car down to the road. Now imagine the car spinning around this pole: the amount of rotation is the yaw of the vehicle. The ECU uses the data from the yaw rate sensor to determine if the vehicle rotates too much: over-steer condition, or if the vehicle does not rotates enough: under-steer condition. The yaw rate sensor is based upon a vibrating cylinder-gyrometer. The metal cylinder is vibrated at a constant frequency. Nodes are displaced depending on amount of vehicle rotation due to the Coriolis Effect. A typical yaw rate sensor is pictured below.

FIG. 7 YAW-RATE SENSOR [BRAKING AND CHASSIS SYSTEMS, WWW.BOSCHUSA.COM]

In addition to the sensors described previously, vehicle stability systems also employ lateral acceleration sensors and brake pressure sensors.

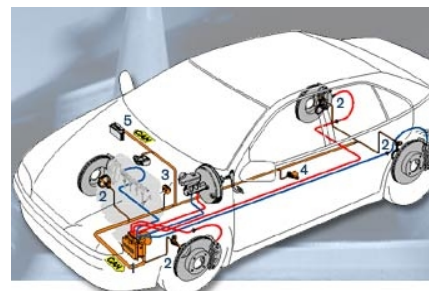The following picture shows the layout of the various ESP components and sensors in a vehicle.

FIG. 8 ESP SYSTEM ON CAN NETWORK

CAN Network

The electronic components in ESP are communicated using a CAN network. CAN, a secure, high speed serial communication standard, developed by BOSCH in the mid 1980's and became a worldwide standard in the early 1990's, is a very cost effective and robust network [CAN networking, www.can.bosch.com]. Currently, CAN is the most widely used standard for networking in automotive applications. Because CAN

is used in so many automotive applications, systems such as ESP are able to interact with other on-board vehicle systems using CAN such as engine and transmission controllers.

CAN is faster than earlier serial communication protocols in the automotive industry such as J1850. High speed CAN is able to reach transfer speeds in the 500kbytes – 1Mbyte/s range. Such high data speeds make CAN an excellent choice for safety critical systems such as ESP.

CAN uses an event triggered protocol. The system will experience peak loads when transmission of multiple messages is requested at the same time. CAN utilizes non-destructive arbitration—all messages will eventually be transmitted. Because CAN uses a non-destructive arbitration, the system must have sufficient processing power to meet all transmission deadlines during peak loads [CAN networking, www.can.bosch.com]. This is especially critical for hard real-time systems such as ESP, because any missed deadline during peak bus loads would result in complete system failure.

The order of transmission when multiple messages are sent is based upon a pre-defined priority. This method of transmission leads to one significant drawback during peak bus loads: unpredictable latency. Because there is no specific piece of transmission time set aside for each message, lower priority messages must keep until all higher priority messages have been sent before they are given control of the bus. Depending on the amount of load on the bus, some lower priority messages may have to keep a couple of seconds before transmitting. Because of this unpredictable latency, it is imperative for hard real-time systems like ESP that a scheduling analysis of the whole system has to be done to ensure that all transmission deadlines are met even at peak bus loads [CAN networking, www.can.bosch.com]. This means that special care should be taken when a microprocessor for ESP is selected. The processor should have plenty of spare capacity even during peak load times to make sure there are no delays for system critical messages.

System Operation

ESP works to prevent a vehicle from skidding out of control. Every 40 ms the ESP system evaluates where the driver is steering the vehicle and where the vehicle is actually going. When vehicle instability is imminent due to over-steering or under-steering, the ESP system reacts by selectively breaking the wheels individually

and managing the engine output. By controlling the amount of slip at each wheel and the amount of torque produced by the engine, ESP is able to stabilize the vehicle giving the driver control of the vehicle in critical situations [Braking and Chassis Systems, www.boschusa.com].
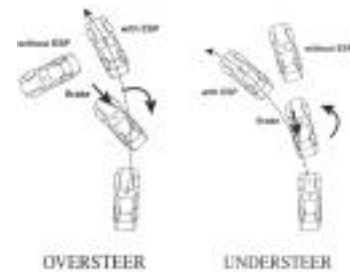

FIG. 9 OVER STEER AND UNDER STEER OF A VEHICLE

During a right hand turn, if the system detects an over-steer condition, it will apply brake pressure to the left front wheel. If the system detects an under-steer condition, then it will apply pressure to the right rear wheel [Van Zanten et al. (1999)]. ESP helps the driver to avoid serious accidents caused by skidding or swerving.

In addition to controlling the vehicle by applying brake pressure, the ESP system also interacts with the engine management system by communicating with the engine control unit. The engine controller is also an embedded system that is responsible for such tasks as fuel injection, spark timing, throttle control and air/fuel ratio. By sending control signals to the engine controller, ESP is able to adjust the amount of torque applied to the wheels. Even though the driver is fully depressing the accelerator, ESP may decide that a reduction in wheel torque is necessary to stabilize the vehicle.
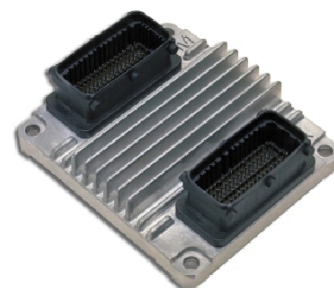

FIG. 10 ON-BOARD ENGINE CONTROLLER [ELECTRIC STEERING SYSTEMS, WWW.DELPHI.COM]

Real-Time System Issues

At its most basic level, a system is one or more inputs entering a device and one or more outputs leaving a device. In the case of ESP, the approximate number of inputs is 11:

1. Brake Master Cylinder Pressure
2. Brake Light Signal
3. Lateral Acceleration
4. Wheel Speed (4)
5. Yaw Rate
6. Park Brake Switch
7. Steering Wheel Angle
8. ESP On/Off Switch
9. Brake Fluid Level
10. Accel. Pedal Position
11. Transmission Status

The ESP system uses the input information to determines the current state and desired state (driver input) of the vehicle. From these inputs, the system will generate a set of primary output signals to adjust the state of the vehicle:

1. Hydraulic Control (brakes)
    a. self-priming recirc pump
    b. precharge pump
    c. inlet valve
    d. outlet valve
    e. pressure limiting EM valve
    f. high pressure suction valve
    g. accumulator
2. Engine Management Signals
    a. spark timing
    b. throttle control
    c. fuel injection
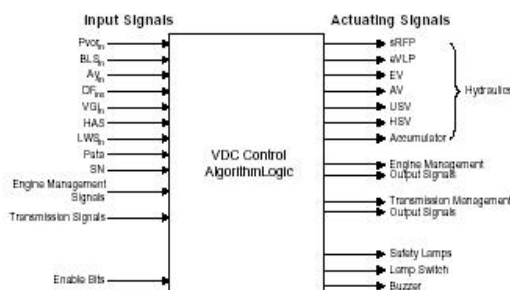3. Transmission Management
4. Driver Information Signals

FIG. 11 ESP I/O DIAGRAM [VAN ZANTEN ET AL. (1998)]

The ESP controller calculates the signals for up to 21 actuators (12 valves, pump motor, engine and transmission controls, 3 driver information lamps, buzzer, and ON/OFF switch for ESP) which modify

the tire forces or inform the driver. In the event of a failure, the ESP system may use these actuators improperly; therefore the system should be designed to avoid such malfunctions [Van Zanten et al. (1999)].

ESP uses both a polling and interrupt driven I/O method. The polling occurs every 40 ms as the system collects data from all of the sensors and modules. These tasks are quietly running in the background completely imperceptible to the driver. The main ECU is also constantly monitoring individual system components for faults and failures. Aside from collecting data from the sensors, the system is primarily interrupt driven. When a critical situation occurs, the system immediately takes action regardless of what time-based task takes place. The time-based tasks are suspended until all critical service routines are completed.

ESP is truly an embedded system with almost no input from the user. There is no keyboard or mouse or monitor. The only controllable interface that the driver has is the ESP on/off switch. Additional user interfaces would include the ESP signal in the cluster to alert the driver that the system is active or that there is an error with the system.

ESP is a complex system working under very stringent timing requirements. Every 40 ms the system must sample the input signals and determine the current state of the vehicle. In those instances when the system detects a critical condition, it will begin to respond before the driver is even aware of that the vehicle is steering out of control. Time is of the utmost importance, because any delay in the system's response could have disastrous consequences for the driver. When driving at highway speeds under icy or wet conditions, a tenth of a second could mean the difference between slamming into a guardrail and safely staying in your lane.

ESP should be classified as a hard real-time system. The system must meet strict timing requirements during operation. The principle value of ESP is its ability to react and stabilize the vehicle faster than human being. Some state of the art ESP systems is able to activate at a rate of 150 times/sec or every 7ms. This is far better than the fastest human response of 300 ms [Braking and Chassis Systems, www.boschusa.com]. In most cases, ESP identifies the critical situation and reacts before the driver is even aware of that the vehicle is out of control [Braking and Chassis Systems,

www.boschusa.com]. If the system were to consistently miss its timing deadlines, then there would be no use for such a system.

If the ESP system fails to meet a timing deadline, then the system has failed entirely. The system's inability to meet response time requirements could have disastrous consequences for both the driver of the vehicle and other drivers on the road. In some instances, failing to meet timing deadlines could result in death or serious injury to vehicle occupants. Because of this, ESP is a hard real-time system, and special precautions must be taken during system designed to ensure the system's ability to meet response time requirements.

Control Structure

The flow of control for ESP begins with the driver's input and current vehicle status. The following data is gathered from the sensors and sent to the ECU: steering angle, yaw rate, wheel speed, lateral acceleration, acceleration pedal pressure, brake pedal pressure, brake fluid pressure, and engine management information. From this information, the ECU calculates the actual motion of the vehicle. In addition to calculating the actual motion of the vehicle, the ECU must also determine the nominal or desired motion of the vehicle. The nominal motion of the vehicle is calculated primarily based on driver input information: steering angle sensor, throttle position sensor, brake pedal sensor. The nominal motion is where the driver would "want" the vehicle to go were it not for the environmental conditions such as a slippery road causing the vehicle to steer out of control.

The ESP controller compares the nominal values for vehicle motion with the actual values for vehicle motion. Once the difference in these two values is determined, the ESP controller determines the corrections in the tire slip values that are necessary to achieve the nominal value for vehicle motion [Van Zanten et al. (1999)]. The overall control of the vehicle is based upon the slip values for all four wheels. Tire slip is the difference between the speed of the tire and the actual speed of the vehicle. If the tire is spinning faster than the vehicle that is moving, then the tire experiences slip.

The corrections in the tire slip values are then sent to an internal module of the ESP controller. This module is called the slip controller. Based upon the corrections

in the tire slip values that need to be made, the slip controller will then determine the control signals that need to be sent to the system's actuators (valves, pumps, etc) in order to achieve the desired tire slip values [Van Zanten et al. (1999)]. The slip controller sends these control signals to the various actuators to change the motion of the tires. Below is the flow of control data for the slip controller.
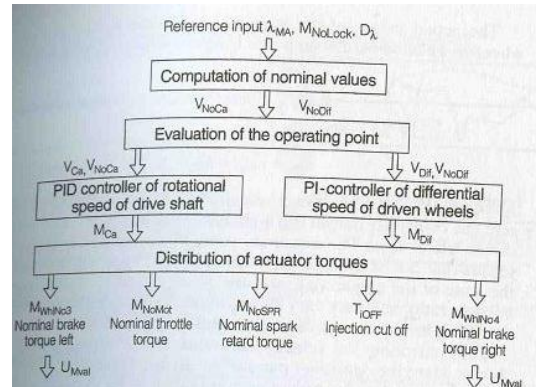

FIG. 12 SLIP CONTROLLER DATA FLOW [VAN ZANTEN ET AL. (1999)]

Control of ESP operates under a dual feedback loop system. There is an outer control loop and an inner control loop. The outer feedback loop calculates corrections in the nominal slip values of the tires from the difference between the nominal and actual motion of the vehicle. These corrections are sent to the inner feedback loop which derives the control signals for the actuators to adjust the tire slip to the nominal values [Van Zanten et al. (1999)].
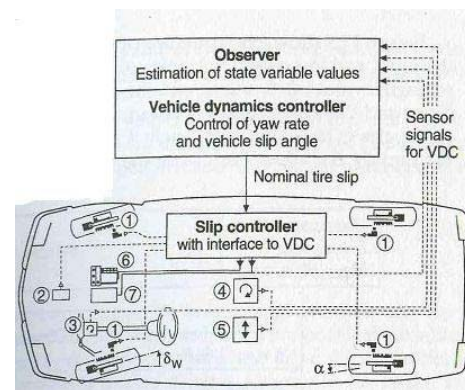

FIG. 13 DUAL LOOP CONTROL CONCEPT [VAN ZANTEN ET AL. (1999)]

Pictured below is the fundamental control task for the ESP system. The vehicle is the plant. The sensors transmit information to determine both the nominal and actual behavior of the vehicle. By comparing the actual behavior with nominal behavior of the vehicle corrections to the tire, slip values can be determined. Actuator control signals derived from the tire slip

values are sent to the various actuators in the vehicle to initiate brake and engine interventions [Van Zanten et al. (1999)].
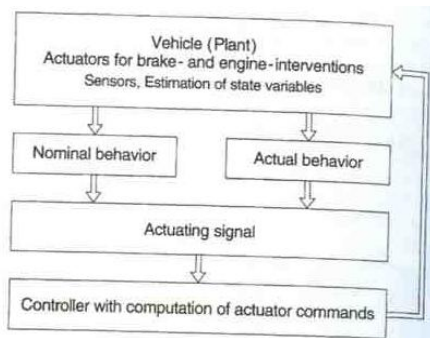

FIG. 14 FUNDAMENTAL CONTROL TASK [VAN ZANTEN ET AL. (1999)]

Safety and Robustness

There are several key safety issues that play an important role in the design and evaluation in a hard real-time system like ESP. One of the most important issues is integration and validation of the system components: sensors, ECU, hydraulic components. Oftentimes, the components are manufactured by various suppliers and may have proprietary interfaces or internal software that must be adapted to work with other components. Some of the electronic modules are not designed for ESP applications. Their operations must be validated and their interfaces have to be adapted to the ESP system [Van Zanten et al. (1999)].

As true with any system made of various modules, ESP is only as good as its weakest component. For this reason, each component must be tested and verified to make sure that it meets the strict safety and timing requirements for an ESP system.

Another challenge faced by suppliers of ESP systems is vehicle variation. Since driving characteristics and other components can vary greatly from vehicle to vehicle, ESP will have to be reconfigured and validated for each vehicle.

There are two types of system shutdowns that can be used for ESP: soft or hard [Van Zanten et al. (1999)]. The system must be able to evaluate the appropriateness of the type of shutdown to be used. In the event that the vehicle is driven at highway speeds, a hard shutdown should be avoided if possible. On the other hand, if the system detects a severe failure while the vehicle is stopped then a hard shutdown may be used in the form of limp-home or walk-home.

Limp-home mode utilizes the engine management system to restrict the vehicle's speed below 20mph. This is one advantage of ESP and the engine management system sharing the same vehicle network.

When the system determines that a system failure is severe enough and that the driver's safety is in danger then it would create a walk-home condition, another hard shutdown. Using the engine management system, ESP would prevent the engine from starting entirely, forcing the driver to "walk home." Such a system shutdown would only be used in the worst case scenario.

In addition, because failure of the ESP system could have such disastrous consequences steps have been taken to ensure partial functionality of the ESP system even when failure occurs. This would be a soft system shutdown. Instead of completely switching off the system in the event of a failure, certain key elements like ABS will remain functioning. For example, if the system discovers a failure in the engine management interface, then that portion of the system would be suspended and the system would only operate during braking [Van Zanten et al. (1999)]. Such steps have been taken to increase the system's robustness and fault tolerance.

As with any system like ESP, a thorough Design Failure Mode and Effects Analysis (DFMEA) should be completed during system design and testing. This would allow for built-in corrective measures based on the analysis of potential problems resulting from failures [Van Zanten et al. (1999)].

One important feature found in the ESP software is model-based sensor monitoring. This type of sensor monitoring is able to detect failures that are only slightly out of specification. Model-based sensor monitoring operates by comparing the actual output of the sensor with a predicted output calculated by a software model [Van Zanten et al. (1999)]. The software tracks the history of the sensor's output and determines the possibility of current readings based upon a model. Once the controller has detected a sensor that operates out of spec, then the controller is able to decrease its own level of sensitivity to that sensor. In other words, when a sensor is under suspicion of failure, the system's magnitude of response to that sensor may decrease dramatically [Van Zanten et al. (1999)].
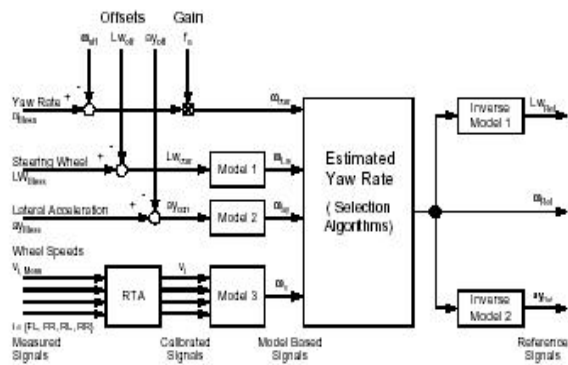
FIG. 15 MODEL-BASED SENSOR MONITORING DIAGRAM [VAN ZANTEN ET AL. (1999)]

These are just some of the techniques used by engineers and designers to increase the safety and reliability of vehicle stability control systems.

Future Trends in ESP

As long as the number of embedded systems in automotive applications continues to grow so will the possibilities of ESP or vehicle stability. With every vehicle system or function that replaces mechanical control with electronic control, ESP has another opportunity to increase its capability and performance. The future of ESP will be dictated by advances in embedded systems for other automotive applications.

Two of the most significant advancements that will affect the future of ESP are the development of steer-by-wire and brake-by-wire systems. Removal of the mechanical element from steering and braking would allow ESP to have full control over braking and steering during a critical situation.

Brake-By-Wire

True brake-by-wire is also referred to as EMB, or electro-mechanical brake. Another form of brake-by-wire is electro-hydraulic brake, but this system uses traditional methods to apply pressure to the brakes via fluid. For this discussion EMB will be the focus when referring to brake-by-wire.

EMB eliminates brake fluid and hydraulic lines entirely. The braking force is generated directly at each wheel by high performance electric motors. These motors are controlled by a central ECU and activated by electrical signals sent from the ECU in response to the electronic pedal module [Brake-By-Wire Technologies, www.conti-online.com]. Below is the brake-by-wire system architecture with the 4 brake actuators on a dual TTP bus.
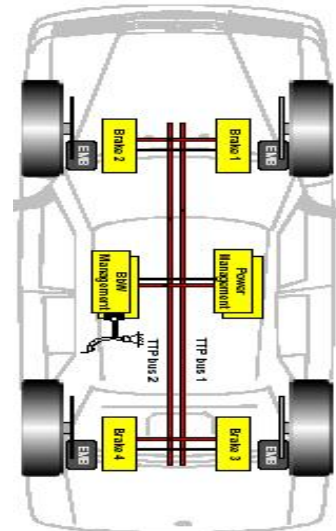

FIG. 16 EMB SYSTEM ARCHITECTURE [HEDENETZ & BELSCHNER (1998)]

EMB is a hard real-time system. Any kind of system delay or failure could have disastrous, in some cases fatal results for the driver of the vehicle. Without room for error during system operation, special care must be taken during system design to ensure robustness and reliability under all conditions.

There is no physical connection between the brake pedal and the brakes. This mechanical connection has been replaced by an electronic signal sent over a bus. Without physical connection to the brakes, an electronic actuator must be placed on the brake pedal to simulate the mechanical feedback to the driver. Consumers would never accept a braking system that lacks the normal "feel" associated with braking. Because braking is such a safety critical system, this kind of brake-by-wire system would have to use a fault tolerant bus such as TTP protocol [Hedenetz & Belschner (1998)].

TTP is a time triggered protocol specifically designed for Class C automotive applications in which any kind of system failure could result in death or injury to the driver. The network consists of sets of redundant ECU's within each module on the bus. TTP is an ideal choice for hard real-time systems like brake-by-wire that cannot tolerate a single point of failure within the network. The diagram below shows the fault tolerant units (FTU) that are made of two or more separate ECU's to ensure continued system operation even if one of the ECU's within the FTU were to fail. In addition, TTP operates using a TDMA (time division multiple access) principle. Each module has its own TDMA slot where it controls the entire capacity of the

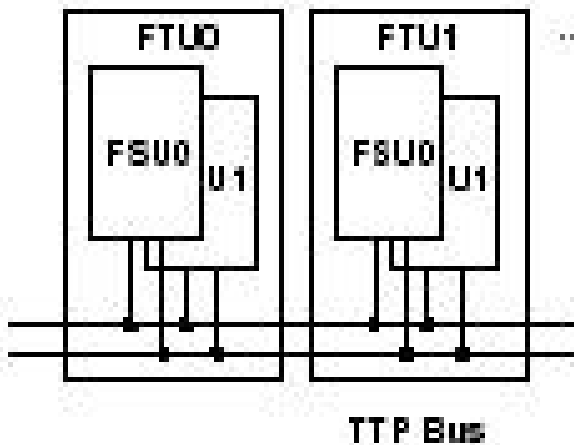network [Microcontroller Family User's Manual (1995)].

FIG. 17 2 FTU'S ON TTP BUS [HEDENETZ & BELSCHNER (1998)]

True brake-by-wire on a vehicle would allow a system such as ESP even greater control of the vehicle during operation. ESP would no longer be constrained by the physical limitations of hydraulic braking. There would be almost no time delay waiting for fluid pressure to build up when ESP activates. This shortened response time is extremely valuable for a hard real-time system like ESP. The fraction of a second that traditional brakes require to begin activation means the difference between staying on an icy road and ending up in a ditch.

Because EMB is on the vehicle bus and supports communication protocols such as CAN, this would allow for much easier integration with other vehicle systems such as ESP ["Electromechanical Braking (EMB)", www.freescale.com]. The ESP and EMB controller could be integrated into a single module thus eliminating data EMB would greatly improve the performance of ESP. Integrating EMB into a vehicle stability system would decrease response times, decrease braking distances, eliminate mechanical braking anomalies, improve system communication and overall system performance. As the number of embedded systems in the vehicle increases, so do the possibilities for total vehicle control.

EMB takes one more element of vehicle control away from the driver and gives that control to a computer. There are risks associated with moving automobile safety in this direction. Drivers will place more and more their trust in embedded systems and rely less and less on their own driving ability. Such issues must be considered when future automotive electronics are designed and developed.

Steer-By-Wire

Steer-by-wire eliminates the mechanical connection between the driver and the vehicle's front tires. The traditional steering elements are replaced by two actuators positioned in the vehicle's front corners. These actuators receive input from the control module and turn the front wheels per the control module's instructions. The system also uses an electric motor to provide road feedback to the steering wheel [Electric Steering Systems, www.delphi.com].

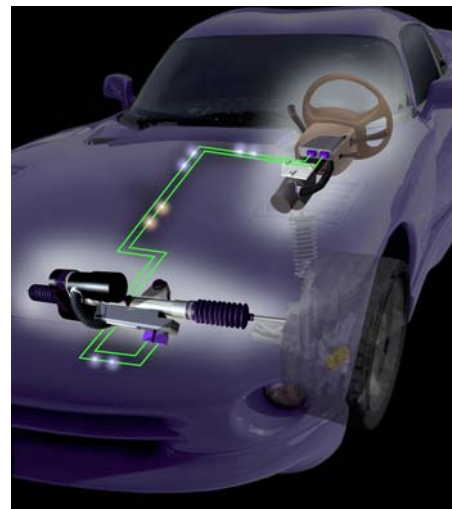FIG. 18 STEER-BY-WIRE [BRAKE-BY-WIRE TECHNOLOGIES, WWW.CONTI-ONLINE.COM]

A true steer-by-wire system offers many advantages over traditional mechanical steering systems. A steer-by-wire has fewer mechanical elements thus reducing vehicle mass and improving fuel economy. Reducing the number of hardware components also simplifies vehicle assembly, improves packaging flexibility and system reliability [Electric Steering Systems, www.delphi.com]. Fewer components improve reliability because there is less chance of system failure due to component failure. Steer-by-wire also improves steering capability in the front wheels resulting in a tighter turning radius [Electric Steering Systems, www.delphi.com]. Steer-by-wire is an embedded system with access to the vehicle network thus allowing easier integration with other vehicle systems such as ESP.

A steer-by-wire system can be subdivided into three major subsystems: a controller subsystem, a driver interface subsystem, and a road wheel subsystem [Kaufmann et al. (2001)]. The figure below depicts the three subsystems of steer-by-wire.
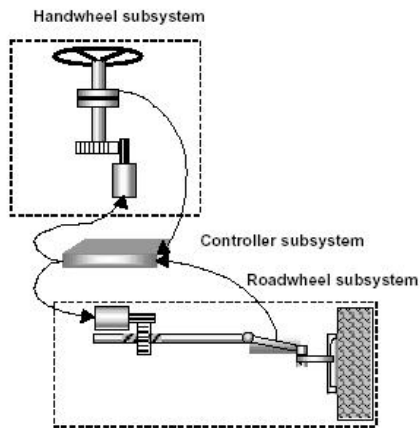
FIG. 19 STEER-BY-WIRE CONCEPTUAL DESIGN [KAUFMANN ET AL. (2001)]

The hand-wheel subsystem provides torque feedback to the driver and position information to the controller based upon the driver's desire position of the steering wheel [Kaufmann et al. (2001)]. The subsystem contains torque sensors and position sensors to measure the force with which the driver turns the wheel and the angle that the driver turns the wheel. In addition, there is a motor mechanism that provides feedback to the driver to simulate the traditional "feel" of mechanical steering. The torque feedback system is necessary for drivers to accept the steer-by-wire system. If there is mechanical feedback coming through the steering wheel, drivers would believe that the car fails to function properly. The torque feedback device is necessary to make steer-by-wire a commercially viable automotive system.
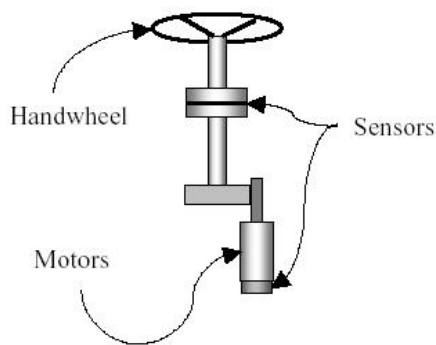

FIG. 20 HAND-WHEEL SUBSYSTEM [KAUFMANN ET AL. (2001)]

The road-wheel subsystem positions the wheels according to input provided by the driver via the hand-wheel subsystem. The input is processed by the controller subsystem. The road-wheel subsystem is also responsible for providing road force information back to the controller subsystem to be used in synthesizing torque feedback to the driver. The controller subsystem calculates the desired hand-

wheel torque and road-wheel position inputs for the other subsystems [Kaufmann et al. (2001)].
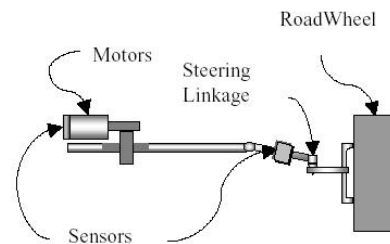

FIG. 21 ROAD-WHEEL SUBSYSTEM [KAUFMANN ET AL. (2001)]

As with brake-by-wire systems discussed previously, steer-by-wire is a safety critical system. Special measures must be taken to ensure the system's robustness and reliability under all conditions. Efforts are made to avoid design errors, limit complexity, avoid common mode failures, continuous maintenance of an acceptable state and support fault-tolerant operation [Kaufmann et al. (2001)]. While steer-by-wire is able to offer much benefit and improve performance, because of its design, it also increases the level of risk for system failure.

Steer-by-wire could be classified as a hard real-time system. Ability to meet response time requirements is critical for a system such as steer-by-wire. There is no backup system to steer the vehicle in the event that the road-wheel actuators are to fail [Kaufmann et al. (2001)]. The system must be designed to be fault tolerant, because any kind of system delay or failure would has disastrous results for the driver.

Steer-by-wire offers much benefit for vehicle stability systems such as ESP. Steering control could be integrated into the ESP system and would remove driver interference during critical situations. Currently drivers are able to "out-steer" the stabilizing ability of the ESP system. In critical situations, a driver might panic and steer the vehicle into an uncontrollable state. ESP is a very effective system, but there are limits to its ability to stabilize the vehicle. Ultimately, ESP cannot defy the laws of physics or a driver determined to steer the vehicle out of control. Having steer-by-wire adds an additional level of control over the vehicle stability system. No longer dependent upon a driver's decision during a critical situation with steer-by-wire, ESP could have total control of the vehicle. ESP would now have the added benefit of controlling the direction and position of the road wheels. Steer-by-wire also opens the possibility of steering each wheel independently if necessary for

the ESP system.

Steer-by-wire would greatly improve the performance of ESP. It is another element of vehicle control that could be integrated into ESP. Just like brake-by-wire, steer-by-wire is another example of by-wire systems increasing the performance and possibilities of vehicle stability systems like ESP.

With steer-by-wire, there are certain risks associated with replacing hard mechanical systems with computer controlled networks. As with brake-by-wire, there are critical issues that must be addressed when an element of vehicle control is taken away from the driver and given over to a computer system. While this transition of control offers almost unlimited potential in terms of safety and control, it also raises concerns on driver responsibility. If a car were to get into an accident, which would be at fault: the driver of the vehicle or the steer-by-wire system manufacturer. Such issues must be weighed carefully when systems like steer-by-wire are designed and implemented.

Recent advances in dependable embedded system technology, as well as continuing demand for improved handling and passive and active safety improvements, have led vehicle manufacturers and suppliers to actively pursue development in computer-controlled by-wire subsystems [Kaufmann et al. (2001)]. Every step of advancement in by-wire subsystems such as brake-by-wire and steer-by-wire is another step towards the development of improved vehicle stability systems. As more and more traditionally mechanical vehicle systems are converted to electronic systems, the ability to integrate these systems with ESP increases. ESP will soon have the ability to completely control many traditionally mechanical systems like steering and braking. This control will increase the performance and capability of ESP.

Advantages and Disadvantages

ESP offering much benefit to vehicle performance and safety, greatly improves a car's ability to steer on icy or slippery roads and also prevents a vehicle from spinning out of control during critical situations, furthermore, it is able to minimize the adverse effects of driving on slippery roads, as well as to recognize when the driver is no longer able to safely control the vehicle and assists in stabilizing the vehicle. When used properly, ESP is capable to assist the driver in avoiding accidents. A driver is immune to helplessness

when veering off the road on a rainy or icy day. When a driver feels that they have lost control over the vehicle, ESP is able to react with brake and engine intervention at a rate over ten times faster than human being. When ESP is viewed as mechanism to assist driver's in critical situation, then it is very beneficial and greatly improves vehicle safety.

While ESP offers drivers much safety and performance benefit, it is important that drivers are aware of the limitations of systems like ESP. The most important rule to remember is that ESP cannot defy the laws of physics. The driver of any vehicle with ESP must keep in mind that there are physical limitations to ESP's ability to stabilize the vehicle. If a driver is going 100 mph and suddenly performs a 90° turn into the guardrail, then ESP may not be able to stabilize the vehicle. It is important for drivers to be aware that ESP will not be able to stabilize the vehicle in all situations. Having a vehicle with ESP may give some drivers a false sense of security about their car's ability to handle inclement condition. In no way is ESP a license to drive recklessly in inclement conditions. This is one potential drawback to ESP.

An additional issue that must be considered with a system like ESP is driver responsibility. As more and more electronic systems replace traditionally mechanical systems, an increasing amount of vehicle control is being given over to embedded systems. While this offers many safety and performance benefits, it also creates a potential hazard. Consumers might become less responsible for their driving and will simply assume that their car will "save." This is a very dangerous trend and all efforts should be made by manufacturers and dealers to reinforce the notion that such systems are simply meant to assist the driver. They were never intended to replace the function of the driver. Control of the vehicle is ultimately the responsibility of the driver. It is important that consumers be informed of the capabilities and limitations of systems like ESP to avoid potentially fatal incidents.

These are some of the positive and negative issues surrounding the development of vehicle safety systems like ESP.

Conclusion

The use of embedded systems in automotive applications has made possible current state of the art safety systems like ESP. ESP uses high tech sensors,

actuators, and microprocessors to provide vehicle stability in adverse driving conditions. Originally introduced by Bosch in 1995, ESP continues to grow both in use and performance. As automotive suppliers continue to find new ways to replace existing mechanical systems with purely electronic ones, the capability of ESP will continue to improve. At the same time, automotive suppliers and manufacturers must carefully way the benefits of such technologies against the inherent risks of computer controlled systems. Perhaps the greatest service that suppliers and manufacturers can perform is to inform consumers of the capabilities and limitations of these systems. These systems will only be effective if drivers are properly informed on how to use them.

REFERENCES

"Bosch Braking Systems", http://www.boschautoparts.co.uk

"Braking Systems", www.trw.com

"Electromechanical Braking (EMB)", www.freescale.com

"The TTP Protocols", http://www.vmars.tuwien.ac.at/ projects/ttp/ttpmain.html

Brake-By-Wire Technologies, www.conti-online.com.

Braking and Chassis Systems, www.boschusa.com.

Cage, Jerry, "Braking Control", Automotive Electronics Handbook, pp. 15.1 – 15.16, 1999.

CAN networking, www.can.bosch.com.

Electric Steering Systems, www.delphi.com.

Gill, Jim, "Electronic Stability Program (ESP) from Continental Teves: Critical Driving Conditions Are Avoided Right from the Start", APR Newswire.

Hedenetz, B., Belschner, R., "Brake-by-Wire Without Mechanical Backup by Using a TTP-Communication Network", SAE International Congress and Exposition, Detroit, Michigan, Feb. 23-26, 1998.

Kaufmann, Tim, Millsap, Scott, Murray, Brian and Petrowski, Jim, "Development Experience with Steer-by-Wire", SAE Future Transportation Technology Conference, Costa Mesa, California, Aug. 20-22, 2001.

Memmer, Scott, "Stability Control: Get Your Yaw-Yaws Out!" www.edmunds.com, 2004.

Microcontroller Family User's Manual, Intel, 8XC196Kx, 8XC196Jx, 87C196CA, 1995.

Sauter, Thomas, "Traction Control", Automotive Electronics Handbook, pp. 16.1 – 16.19, 1999.

Van Zanten, Anton, "Bosch ESP Systems: 5 Years of Experience", SAE Automotive Dynamics & Stability Conference, Troy, Michigan, May 15-17, 2000.

Van Zanten, Anton, Erhardt, Rainer, Landesfeind, Klaus, Pfaff, Georg, "Stability Control", Automotive Electronics Handbook, pp. 17.1 – 17.33, 1999.

Van Zanten, Anton, Erhardt, Rainer, Landesfeind, Klaus, Pfaff, Georg, "VDC Systems Development and Perspective", SAE International Congress and Exposition, Detroit, Michigan, Feb. 23-26, 1998.

www.intel.com/design/auto/chassis.htm

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